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Mission Simulation Memo #2-70

TO: Distribution

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DATE: 18 February 1970

SUBJECT: Powered Landing-Maneuver Navigation over Rough Terrain

Summary

This memo contains a series of viewgraphs prepared for presentation at the design-review meeting held at MSC on February 3, 1970 to consider various "terrain-filtering" schemes for use in the powered landing maneuver. The major results and recommendations are:

(1) A simple a-priori terrain model should be stored in the LGC for use during the approach phase. This results in a smoother LPD-angle profile, and reduces LPD pointing errors.

(2) The altitude weighting function during the braking phase should be reduced from its present value to limit pitch-angle oscillations of the thrust vector.

(3) It is not necessary to include a LR prefilter in the navigation system. Essentially the same effect can be obtained by properly shaping the altitude weighting function.

(4) Essentially the same weighting functions as in the present system should be used during the approach phase in order to keep altitude estimation errors small.

(5) On the basis of statistical simulation results it was found that the best choice of weighting functions, in a minimum mean-squared error sense, was dependent on the altitude-variation characteristics of the actual approach terrain to the site and the a-priori models in the LGC. To provide flexibility under these conditions, a two or three segment altitude weighting function should be used.

(6) It is possible to obtain useful estimates of terrain-datum uncertainty with a fairly simple slope estimator, based on the correlation between terrain-datum error and altitude measurement error ($\tilde{h} - h'$). This estimator can, in certain cases, improve the approach-phase trajectory.

(7) The altitude reasonableness test lockout level must be sufficiently high at the start of P64 so that good LR data are not permanently inhibited.

General Information

The problem is concisely defined in Fig. 1. Of particular importance is the fact that it is desired to estimate not local altitude, but rather altitude w.r.t to the landing site. A major source of difficulty is that the LR measures range to a point on the ground along the range beam rather than range to the landing site.

The key assumptions are given in Fig. 2. The LR acquisition altitude of 35,000 feet for range and 30,000 feet for velocity were considered to be reasonable numbers with the current LR dropout boundaries. The altitude-data reasonableness test was removed for

this study to avoid problems caused by the inhibiting of LR data after High-Gate, if the estimation errors are not sufficiently small at that time.

The basic criteria used to evaluate the navigation system performance during the landing maneuver are given in Fig. 3. In essence, if the altitude estimation errors w.r.t. the site are sufficiently small about one minute before High-Gate and are held down thereafter, then all the various performance indicators will be satisfied. The most important of the performance indicators were found to be the LPD profile, the LPD pointing error, the terminal altitude vs range to go profile, and the thrust-vector elevation-angle profile.

Models for the terrains used in the landing study are given in Fig. 4 as a function of range-to-go, and in Fig. 5 as a function of time. Zero time in Fig. 5 is taken as the time that the full-thrust-position command is nominally issued. The terrain profile seen by the navigation system (Fig. 5) is significantly different from the distance profile (Fig. 4) because of the wide range of vehicle velocities during the landing maneuver. The basic effect is that the number of measurements over a given terrain segment increases as the vehicle slows down en route to the site.

The primary LR data filtering techniques investigated are outlined in Fig. 6. The basic relations for implementing these schemes are given in Figs. 7-10. It should be noted that a terrain-slope estimation option is provided for both Filter #3 (Fig. 9) and Filter #4 (Fig. 10). Also, the values of n and w shown for Filter #3 were preliminary values.

Use of A-Priori Terrain Models in LGC

The possibility of storing a-priori terrain-altitude variation models in the LGC was studied in detail for Censorinus B and C landing sites. The basic models used for the a-priori terrains are shown in Figs. 11 and 12. The major results of the study are summarized in Fig. 13.

An important advantage of using prestored terrains is that the LPD profiles are improved and the pointing errors are reduced. This is demonstrated in Figs. 14 and 15 for Censorinus, using the present navigation system. The advantage of a prestored terrain is shown also in Fig. 16 for a landing at Fra Mauro, using a navigation filter similar to #4-B in Fig. 10.

It should be noted in Fig. 13 that it is suggested that the terrain seen along the range beam should be stored, rather than the local terrain variation. Storing the local terrain can introduce significant errors at long ranges from the site, where the range beam may be 30-40 degrees from local vertical. It should also be noted that it is suggested that the terrain be stored as a function of the down-range distance to the initial site, which will differ from the actual site if redesignations are made.

With the present landing-trajectory targets, it was found that it is better to under-store the terrain rather than to over-store it in the a-priori model, particularly during the approach phase. The important point here is that navigation errors which indicate that the vehicle is higher than it actually is should be avoided.

Performance Comparisons of Candidate Navigation Systems

In order to examine the performance of the various navigation filters described in Fig. 6, a series of simulated landing trajectories were flown over Censorinus B and C with selected combinations of terrain-datum uncertainty, initial velocity estimation errors, and initial altitude estimation errors. Cases with both simple and more complete a-priori terrain models were studied, along with cases where no stored terrains were used. The numerical values used in the test runs were 1 degree for terrain-datum uncertainty, 10 f/s for vertical-velocity estimation error at DDI, and about 2000 ft. for altitude estimation error at the time of LR range acquisition.

A typical set of test data is given in Figs. 17-20 for a Censorinus-C landing with a 1-degree terrain-datum uncertainty, using various candidate navigation filters in combination with a simple

a-priori terrain. Thrust-vector elevation profiles are compared in Fig. 17, LPD characteristics in Fig. 18, and terminal altitude vs. range-to-go profiles are shown in Fig. 19. An evaluation of the relative merits of the different filters based on these data is given in Fig. 20. Also presented in Fig. 20 are comparison data on required ΔV, High-Gate altitude, and LM velocity at an altitude of about 500 feet w.r.t. the site.

The question as to whether a terrain-datum uncertainty should be estimated, is considered in Fig. 21 for Filter #4-B. It has been found that the long baseline uncertainty can be estimated with varying degrees of success. Small local slopes, on the other hand, could not be usefully estimated without introducing other problems. Two extreme cases are shown in Fig. 21: the cases where the terrain-datum estimator most significantly help and hurt the navigation system performance. It should be noted that with a simple a-priori terrain, the major effect is on the terminal altitude or range-to-go profile.

The major results and recommendations are summarized in Fig. 22.

Fig. 1: **Definition of Problem**

- Estimate altitude of LM w.r.t. Landing site
- Primary sensor is LR which measures range to the terrain at which the range beam is pointed
- IMU measures the change in vehicle velocity during powered maneuvers, with alinement & accelerom. bias errors
- At PDI the XP-components of LM position and velocity w.r.t. site are known to about 1000 ft & 1 f/s (1-sigma)
- Local terrain height variations, terrain-datum uncertainty (slope), and LR measurement noise cause the vertical component of the measurement to differ from altitude w.r.t. the site.

Fig.2: <u>Basic Assumptions in Study</u>

- LR acquisition takes place at h=35,000 ft for range measurements and at h=30,000 ft for velocity measurements
- The primary terrain profiles considered were Censorinus B, Censorinus C, and Copernicus
- Terrain-datum uncertainty taken as 1 degree (3-sigma), but with the maximum altitude deviation w.r.t. the site limited to 5000 feet
- Completely-automatic landing with P63, P64, and P65, using the Apollo-12 reference trajectory
- No altitude-data reasonableness test or LR dropout boundaries
- PDI position errors w.r.t. site of 1000 ft down-range and 1500 ft cross-range with N69 (1-sigma); down-range of 4000 ft with no N69 (1-sigma)

Fig. 3: Performance Evaluation Criteria

- Minimize the error in the estimate of LM altitude w.r.t. the landing site: $(r_P - r_M) - (r_T - r_{ST})$
- Above error should be reduced to a reasonably small value by HG and kept small thereafter
- If the altitude estimation error is sufficiently small, good values will be obtained for these perform. indicators:

(1.) ΔV from TIG to TD	(5.) Interval for which LPD ang. < 57°
(2.) LM velocity at $h \approx 500$ ft	(6.) LPD angle profile
(3.) Thrust-vector elev. angle profile	(7.) LPD pointing error
(4.) H vs. r_{GO}, Last 20,000 ft	(8.) Dead-man's curve cross-over point

Fig. 4: Local Terrain Variation vs Range-to-Go

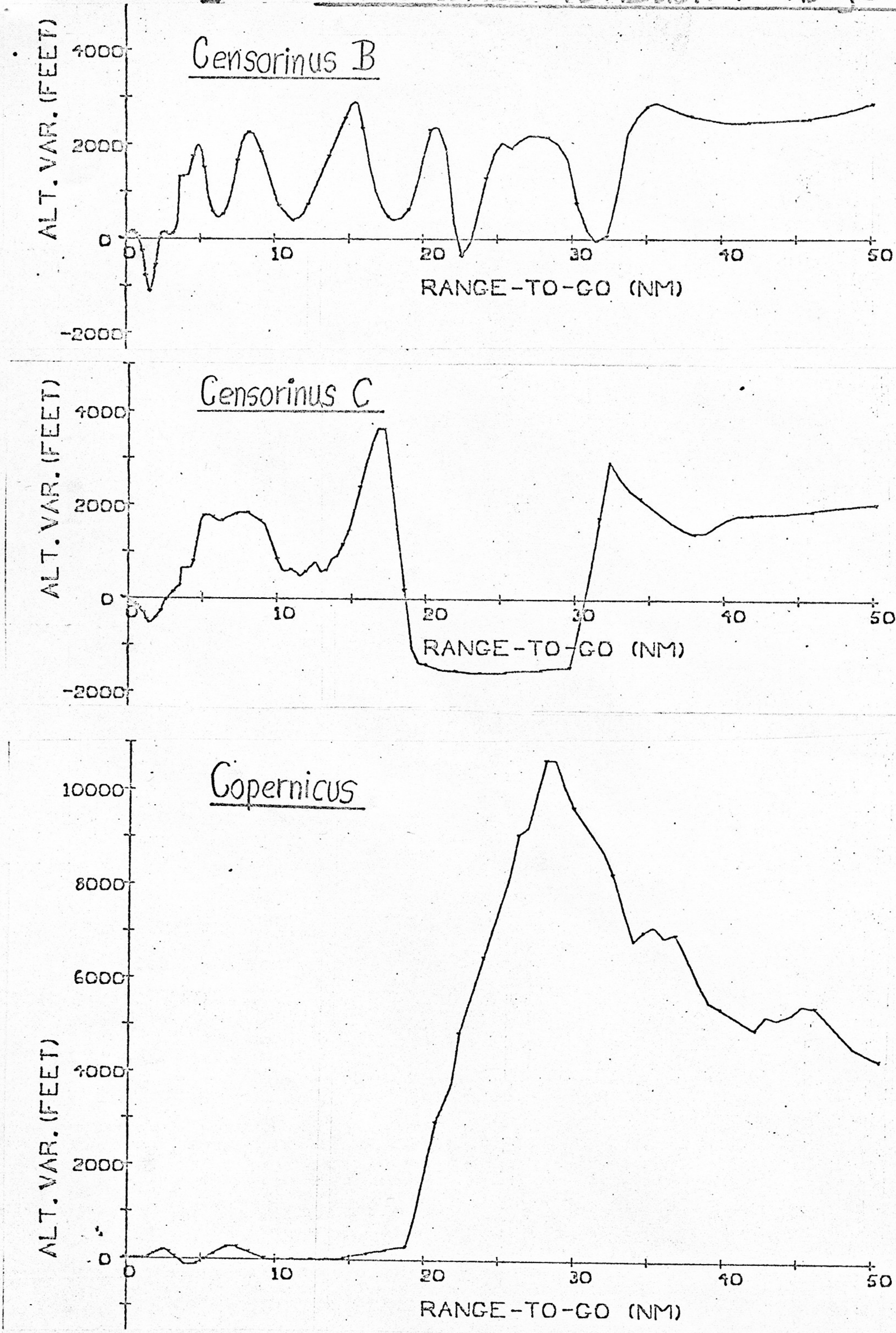


Fig5. Local Terrain Variation vs. Time

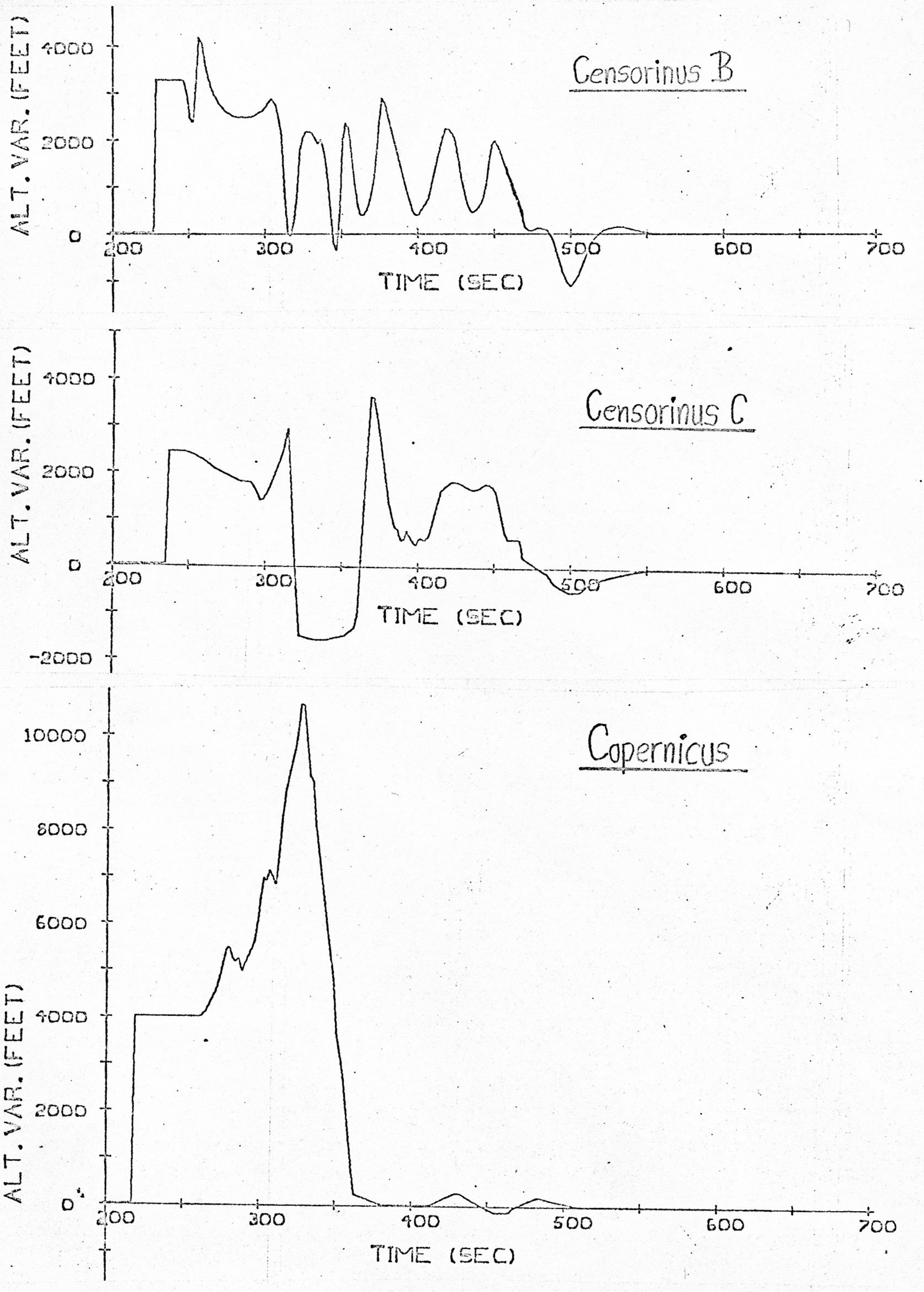


Fig. 6: <u>LR Data Filtering Techniques Studied</u>

Present System	Linear W_H vs h, $W_H = .35$ at $h=0$
Filter #1	Same as present system except $W_H = .10$ at $h=0$
Filter #2	Least-squares smoothing & slope estimation, 30-sample batch processing (LEC Memo ADM/122 by Rozendaal)
Filter #3 (A.)	Simpler & more flexible version of Filter #2 without the slope estimator (T. Moore of MSC, Internal Note MSC-68-EG-05)
(B.)	Slope estimator added to (A)
Filter #4 (A.)	Two segment weighting function: Linear with h from 0 to 0.1 in PG3, and Linear from 0.1 at start of PG4 to 0.25 at $h=0$
(B.)	Simple slope estimator with $W_{SL} = .01/N$ $\left(\frac{ft/n.m}{ft}\right)$ added to (A),

<u>Above filters used with</u>:
(1.) No prestored terrain model
(2.) Simple stored terrain model
(3.) Detailed stored terrain model

Fig. 7: Navigation Equations for Present System

$$h' = r_P - r_{SP}$$

$$\delta h = \tilde{h} - h'$$

$$W = LRWH\left(1 - \frac{h'}{LRHMAX}\right)$$

$$\underline{r}_P = \underline{r}_P + W\,\delta h\,\underline{u}_{HP}$$

Present Erasable Values:

LRWH = 0.35

LRHMAX = 50,000 ft

h' = à-priori LM altitude estimate w.r.t. Landing site

$\underline{r}_P$ = LM position vector

$\underline{r}_{SP}$ = Landing-site position vector ($\underline{r}_{LS}$)

$\tilde{h}$ = LR altitude measurement (slant range projected along loc. vert.)

W = LR altitude weighting function

$\underline{u}_{HP}$ = unit vector along Local vertical

Fig. 8: Filter #2: Basic Equations (LEC)

$$\underbrace{\tilde{h}^*_n}_{\substack{\text{smoothed}\\ \text{alt. meas.}}} = \underbrace{\frac{1}{n}\sum_1^n \left(\tilde{h}_i - \Delta h_{1,i}\right)}_{\substack{\text{ave. dist. from}\\ \text{baseline to terrain}}} + \underbrace{\frac{S_n}{n}\sum_1^n r_{GO_i}}_{\substack{\text{ave. slope}\\ \text{alt. deviation}}} + \underbrace{\Delta h_{1,n}}_{\substack{\text{alt. change from}\\ \text{ref. to pres. alt.}\\ \text{meas. by PIPAS}}}$$

$$S_n = \frac{\sum_1^n \left(\tilde{h}_i - \Delta h_{1,i}\right) r_{GO_i} - \sum_1^n \left(\tilde{h}_i - \Delta h_{1,i}\right) \frac{1}{n} \sum_1^n r_{GO_i}}{\sum_1^n r_{GO_i}^2 - \frac{1}{n}\left(\sum_1^n r_{GO_i}\right)^2}$$

$$\underline{r}_p = \underline{r}_p + W\left(\tilde{h}^* - h'\right)\underline{u}_{HP} \quad , \text{ when } n \geq 30$$

$\tilde{h}_i$ = LR-derived altitude meas.

$\Delta h_{1,i}$ = meas. change in veh. alt. from t_1 to t_i

r_{GO_i} = est. distance-to-go from vehicle to landing site

S_n = est. terrain slope

n = counter

Stored Sums Required

$$\Delta h_{1,n}\ ,\ \sum_1^n r_{GO_i}\ ,\ \sum_1^n r_{GO_i}^2$$

$$\sum_1^n \left(h_i - \Delta h_{1,i}\right),\ \sum_1^n \left(h_i - \Delta h_{1,i}\right) r_{GO_i}$$

Note that:

(1.) Old data are removed from the stored sums periodically, i.e. in 30-sample batches

(2.) Present updating scheme used when $h' < 1500$ ft.

Fig. 9: Filter #3: Navigation Equations (T. Moore)

A.) Smoothing Only

$$\delta h^* = (1-W)\left(\frac{n-1}{n}\right)\delta h^* + \frac{1}{n}(\tilde{h} - h')$$

$$m = m+1$$

$$\underline{r}_P = \underline{r}_P + W\,\delta h^*\,\underline{u}_{HP}$$

m	n	W
1—5	m	0.20
6–29	5	0.20
30—∞	14	0.05

B.) Smoothing and Slope Estimation

$$k = \left(\frac{n\,c}{W} - 1\right) / n\,r_{GO} \quad , W = .05, \; c = .04$$

$$\delta s = k\left[(\tilde{h} - h' - s\,r_{GO}) - (1-W)\,\delta h^*\right]$$

$$\delta h^* = (1-W)\left(\frac{n-1}{n}\right)\delta h^* + \frac{1}{n}(\tilde{h} - h' - s\,r_{GO}) - \delta s\,r_{GO}$$

$$s = s + \delta s$$

$$\underline{r}_P = \underline{r}_P + W\,\delta h^*\,\underline{u}_{HP}$$

$$m = m+1$$

m	n	δs
1—13	m	0
14—∞	14	as computed

Fig. 10: Filter #4: Basic Relations

A.) No slope estimation

$$W_H = LRWH\left(1-\frac{h'}{LRHMAX}\right)$$

$$h' = r_p - r_{SP}$$

$$\delta h = \tilde{h} - h'$$

$$\underline{r}_p = \underline{r}_p + W_H\,\delta h\,\underline{u}_{HP}$$

	P63	P64 & 66
LRWH	0.10	50,000 ft
LRHMAX	0.25	10,000 ft

B.) With slope estimation

$$W_{SL} = \frac{.01}{n}\left(\frac{F/nm}{ft}\right)$$

$$h' = r_p - r_{SP} - S\,r_Z$$

$$r_Z = r_{ZP} - r_{SZP}$$

$$S = S + W_{SL}\,\delta h$$

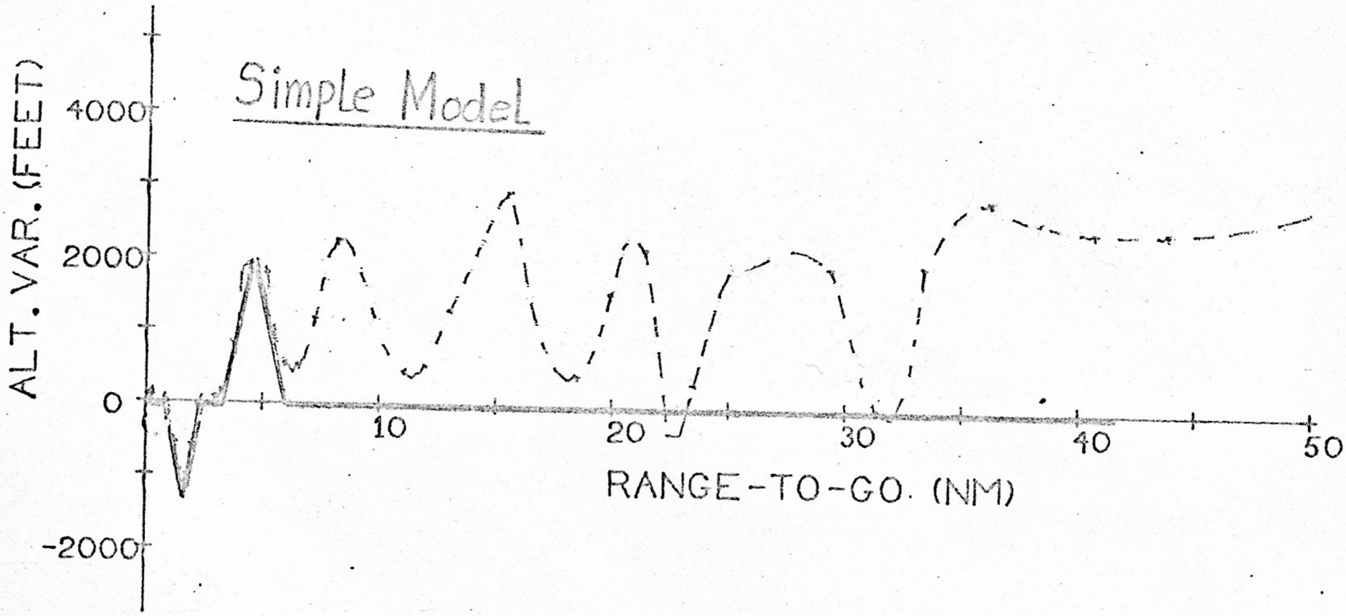
$$n = n+1$$

$$W_H = LRWH\left(1-\frac{h'}{LRHMAX}\right)$$

$$\delta h = \tilde{h} - h'$$

$$\underline{r}_p = \underline{r}_p + W_H\,\delta h\,\underline{u}_{HP}$$

Fig. 11: Stored-Terrain Models for Censorinus-B



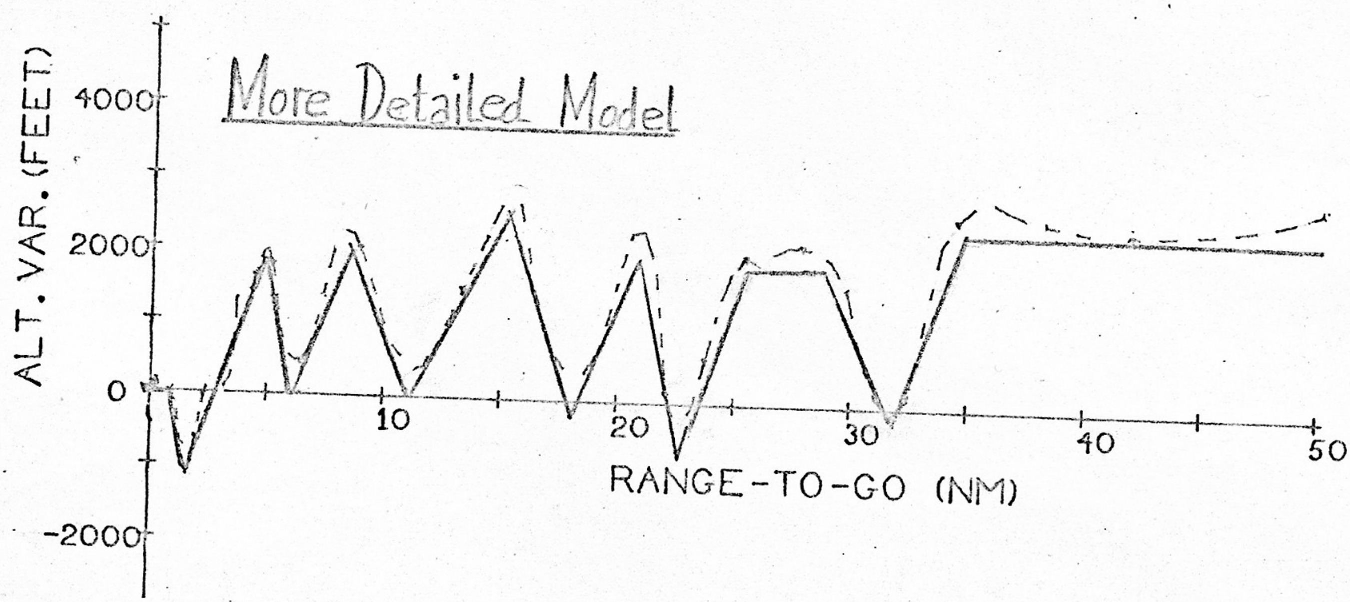
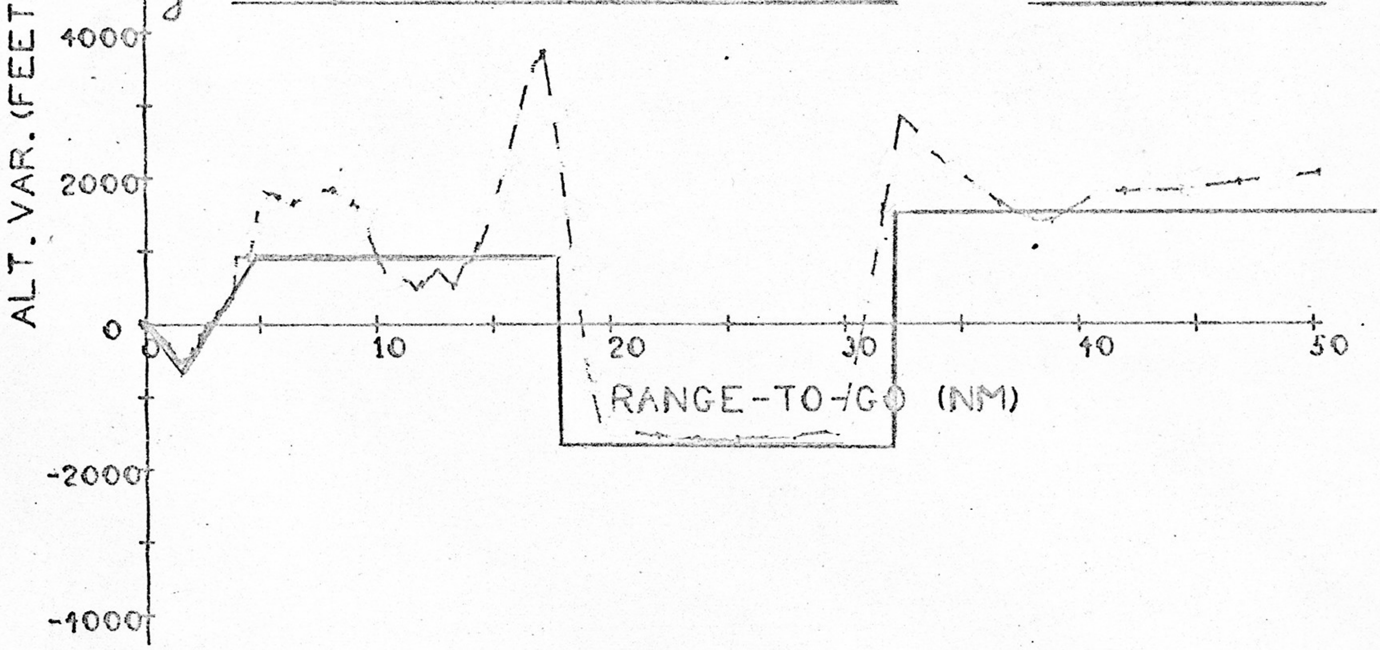


Fig 12: Simple Stored Terrain Model: Censorinus-C



More Complete Stored Terrain Model: Censorinus-C

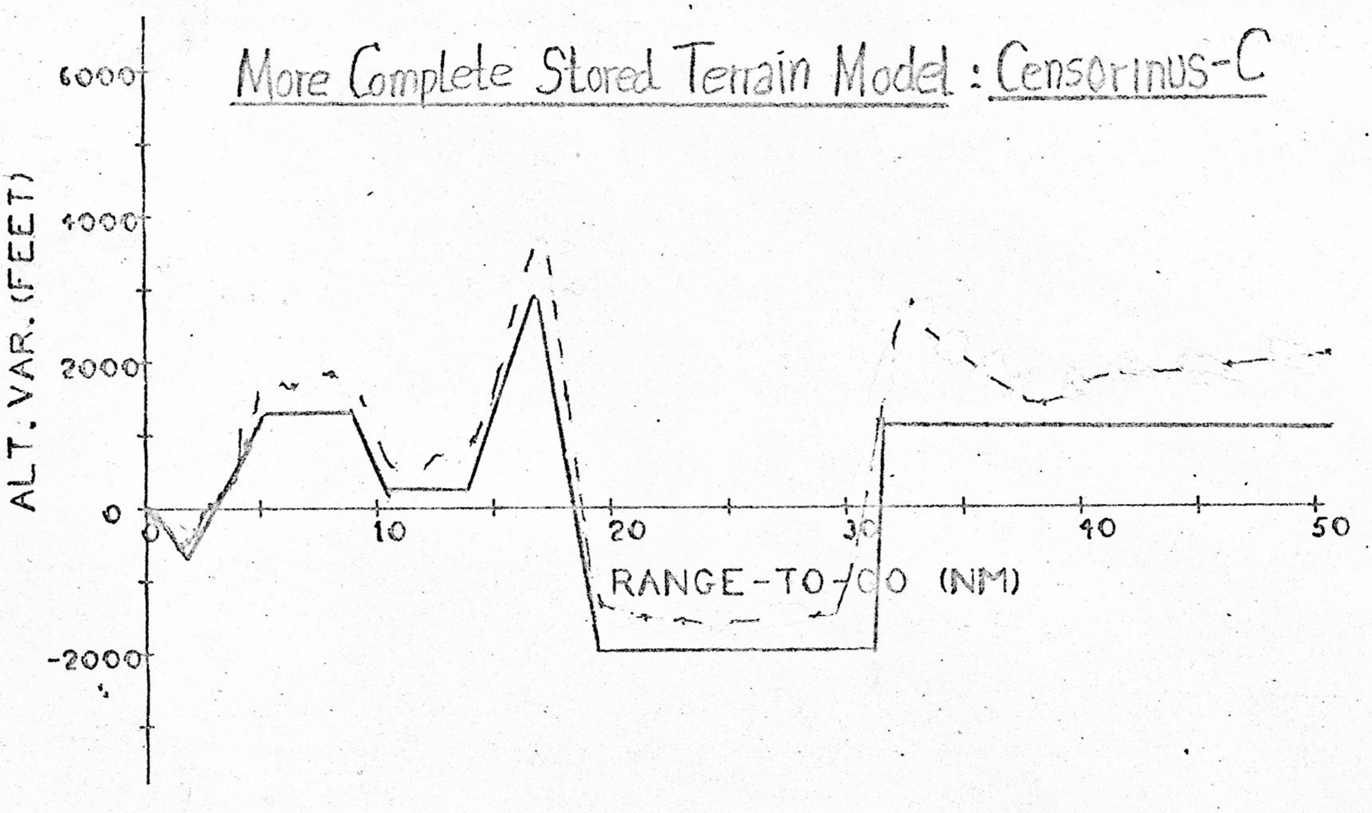


Fig 13: Use of Stored Terrain Models: Result Summary

- Primary effect is improved LPD-angle profile and reduced LPD pointing error in approach phase

- Simple terrain models for Censorinus-B and C adequate for above purpose; more important to store accurately in approach phase than to model in more detail in braking phase

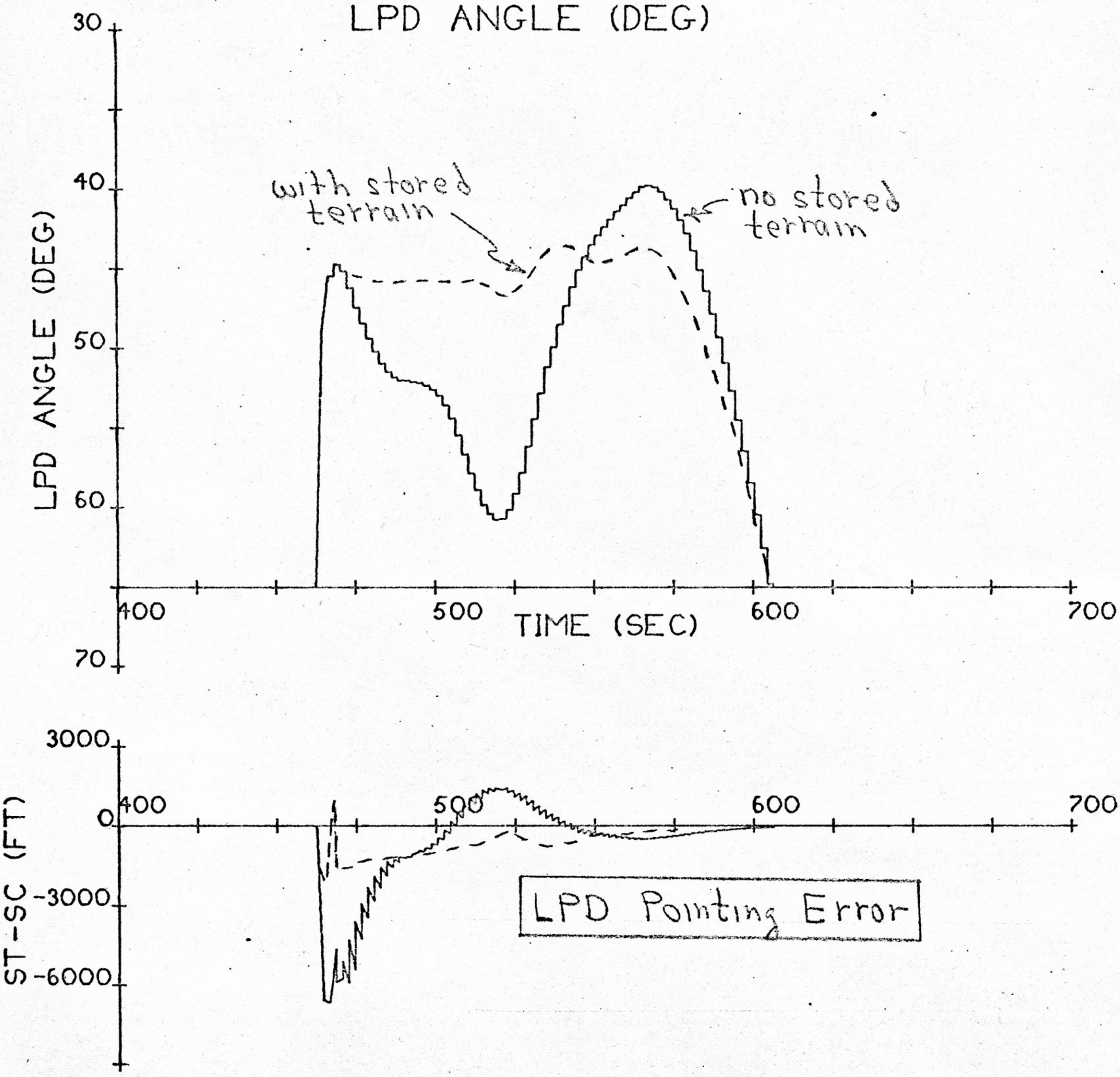
- Store terrain as seen along the range beam on a nominal trajectory; store as a function of the down-range distance to the initial landing site, i.e. vs. $r_{ZP} - r_{SZP}$

- Down-range position estimation errors of up to 4000 ft did not significantly effect the LPD-angle characteristics

- With the present targets it is desirable to under-store to minimize trajectory drooping

Fig. 14: LPD Characteristics With & Without Stored Terrain

present system, Censorinus B, simple stored terrain
+1 deg slope, -10 f/s v.vel. error



RUN NO. = 718

Fig 15: Present System with Various Terrain Models

Censorinus-C, -1-deg slope (up-hill)

-10 f/s vert. vel. est error at PDI

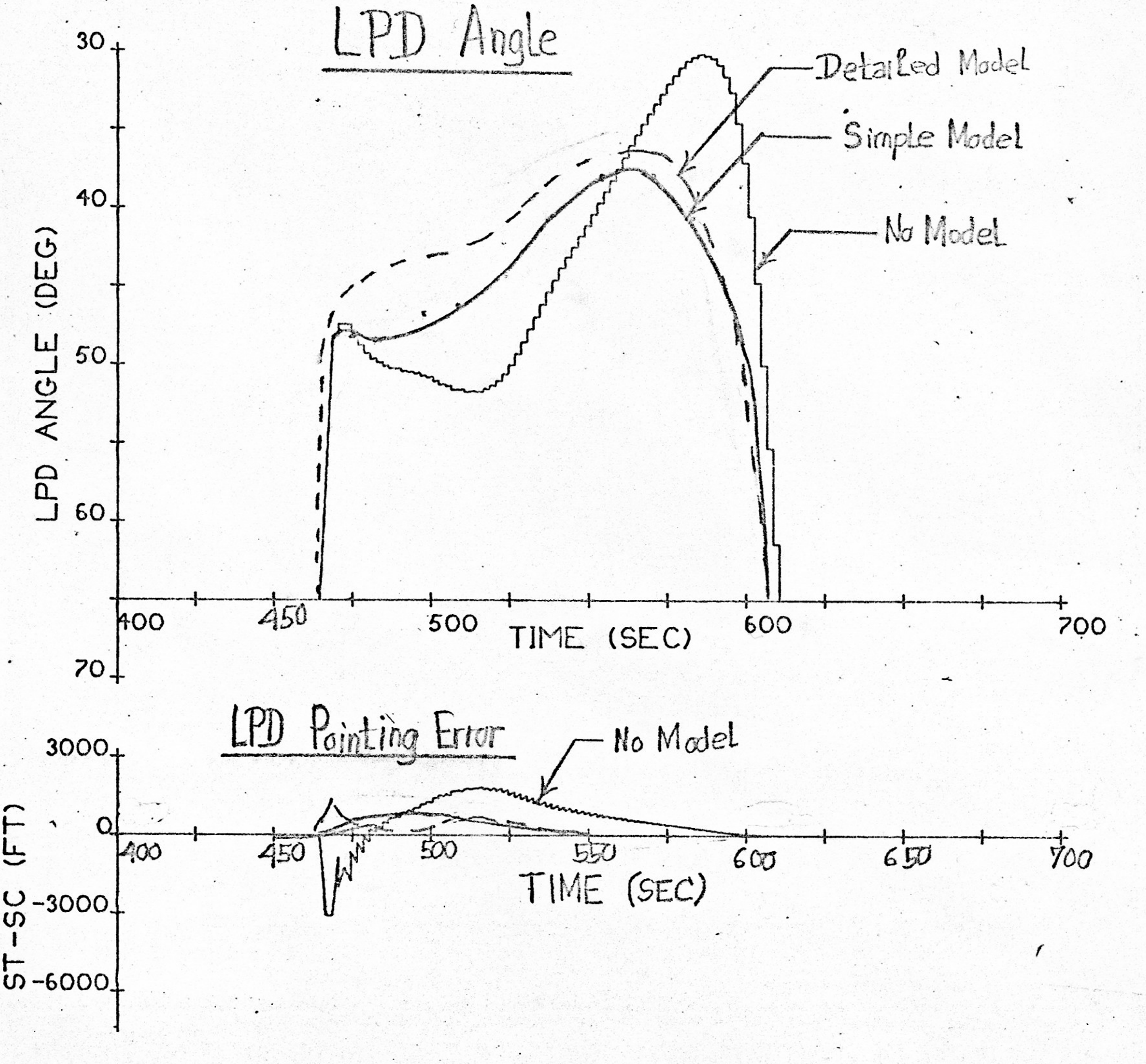
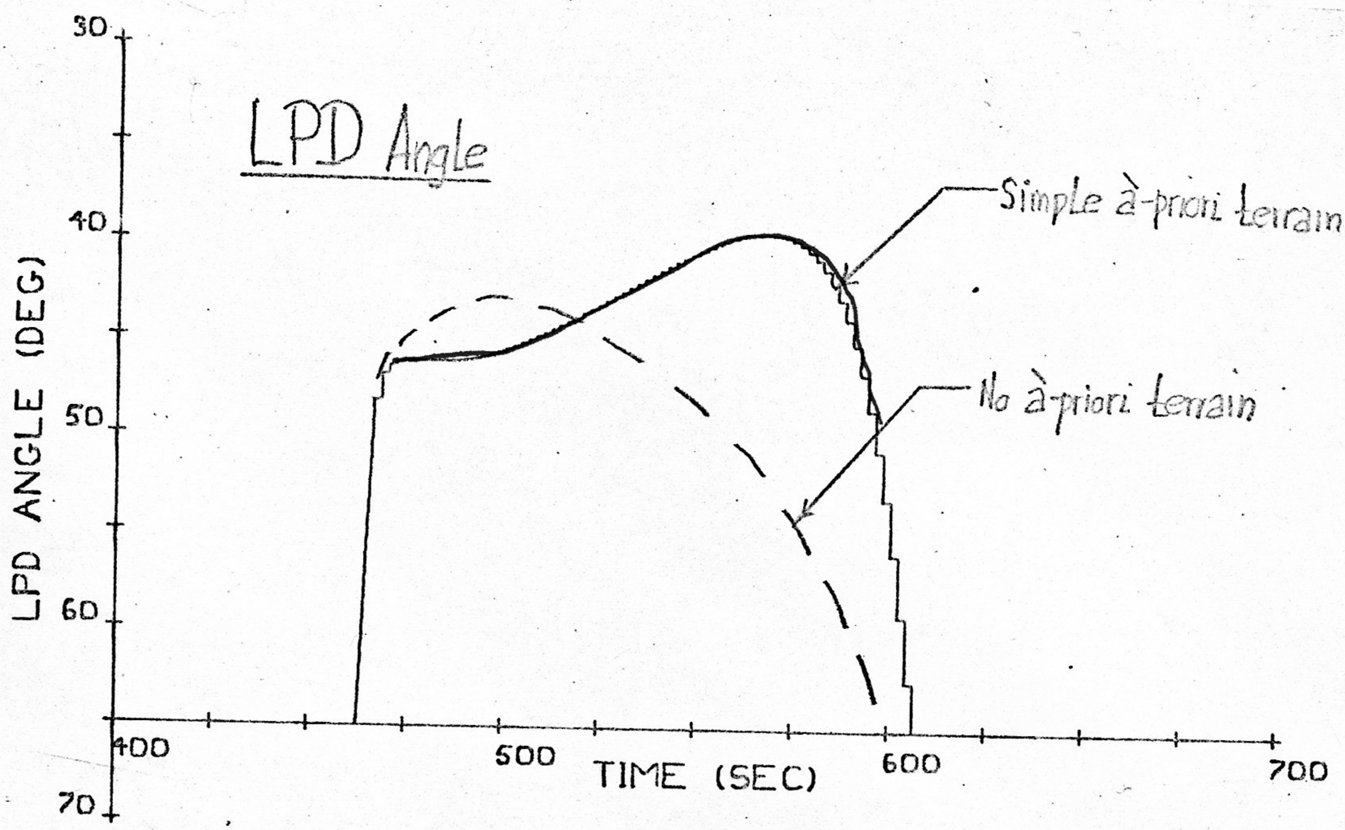


Fig 16: Use of Stored Terrain for Fra Mauro Landing

Nominal, error-free trajectory for Fra Mauro



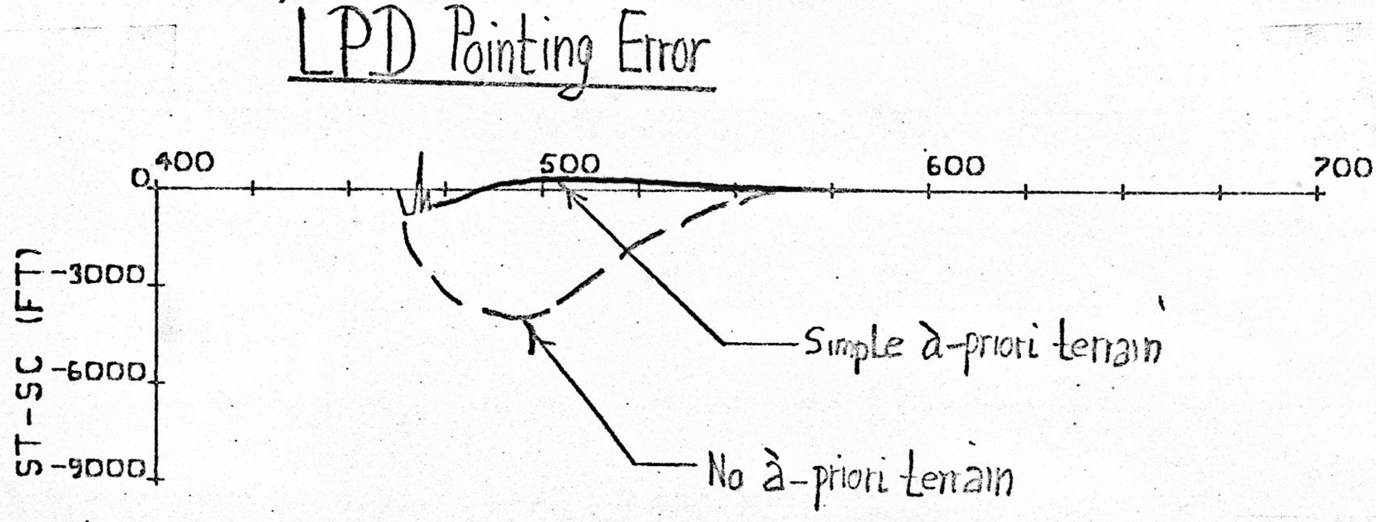


Fig. 17: Thrust-Vector Profiles with Various Filters

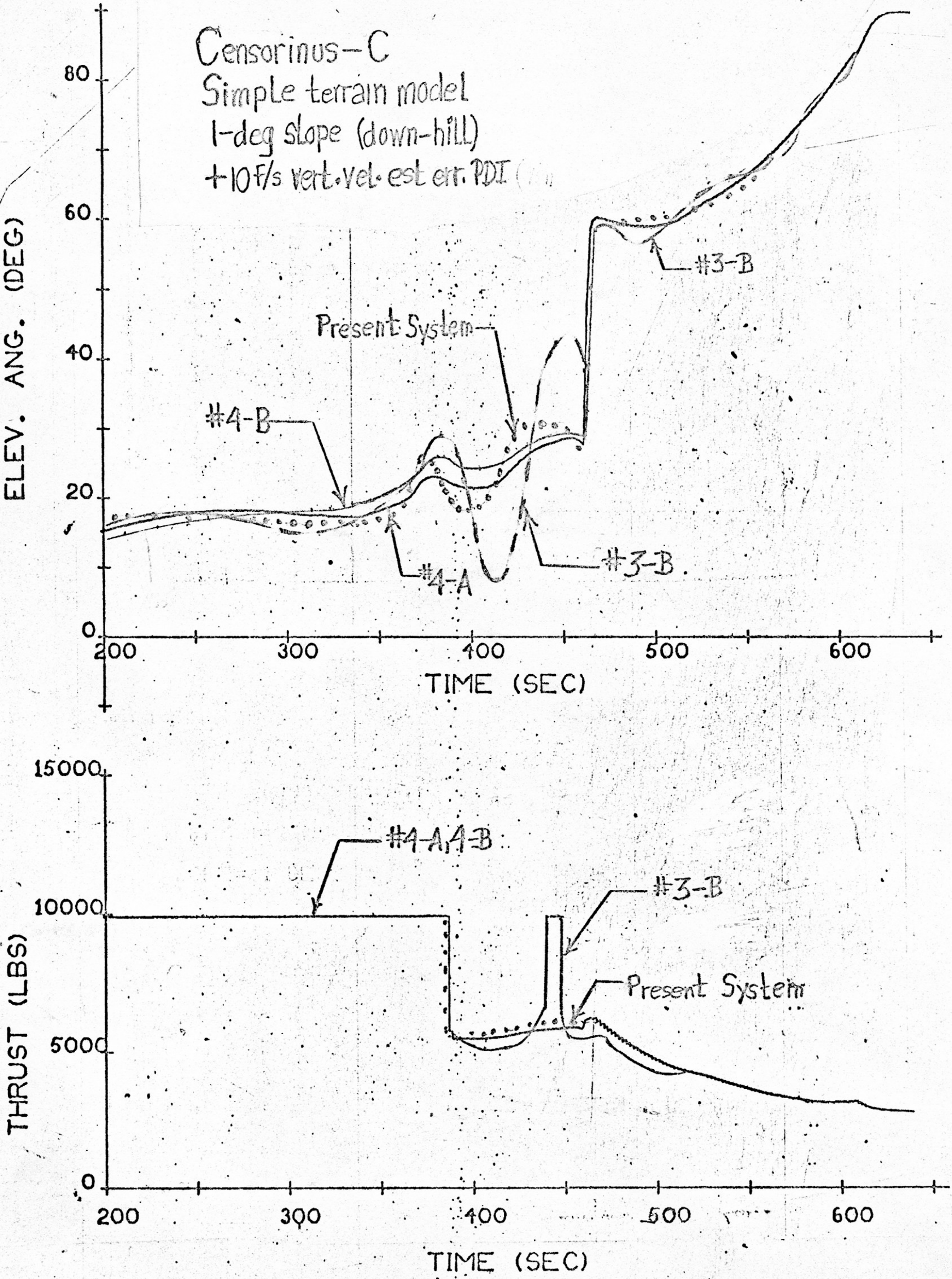
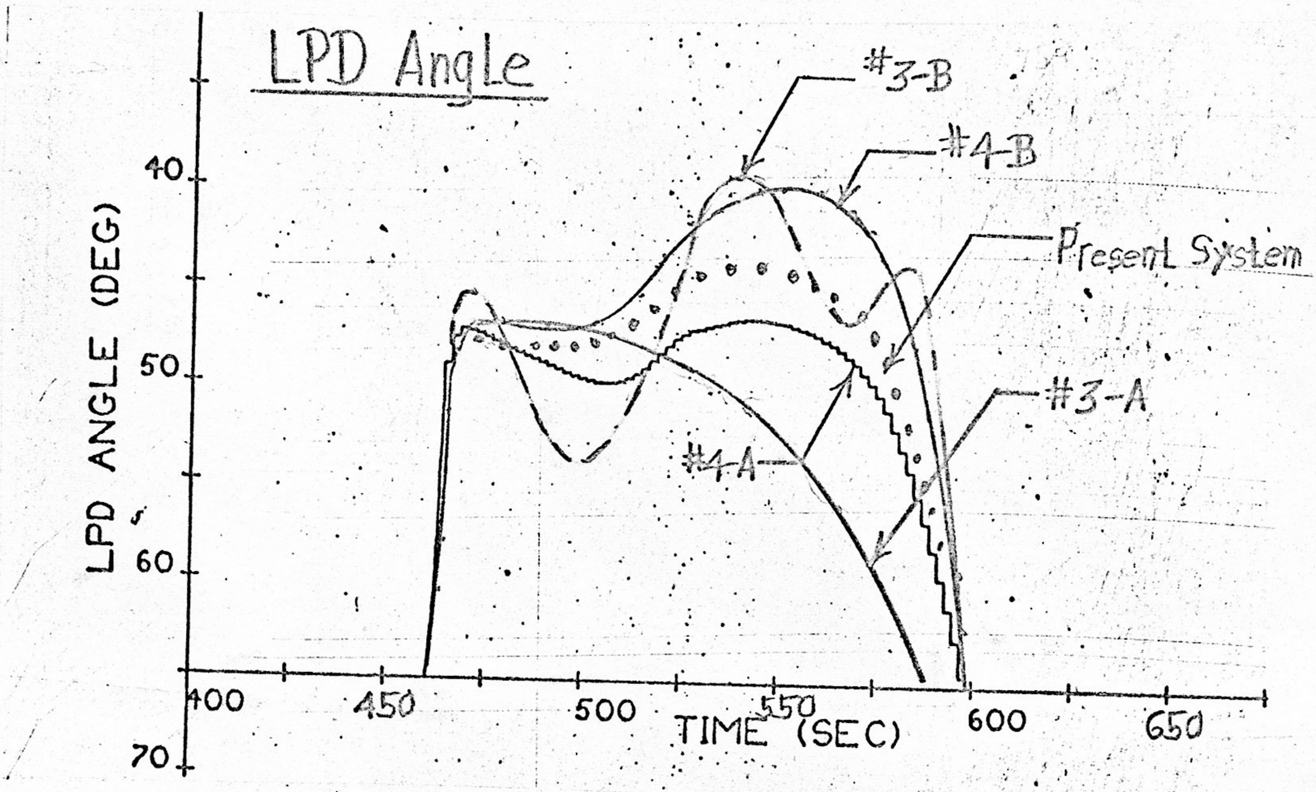


Fig.18 LPD Angle & LPD Pointing Error for Different LR Filters

Censorinus-C, Simple Stored Terrain Model,
+1 Deg Slope (down-hill), +10 F/s vert. vel. est. error PDI



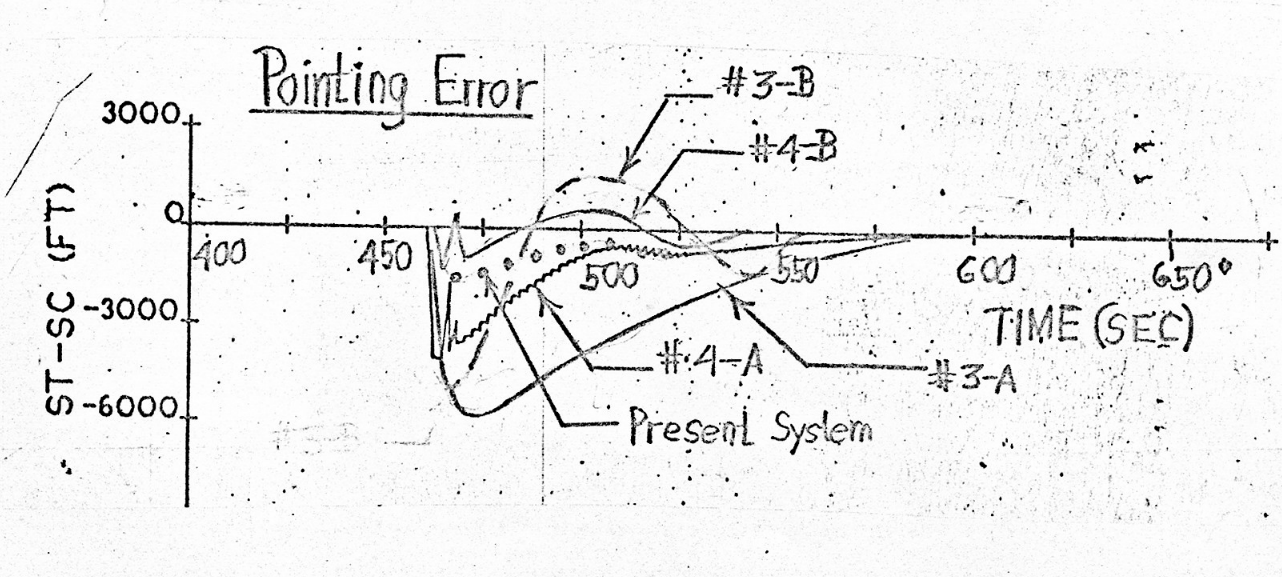


Fig 19: Altitude vs. Range-to-Go for Various Filters

Censorinus-C, Simple terrain models

+1 degree slope, +10 ft/s vert vel. est. error at PDI

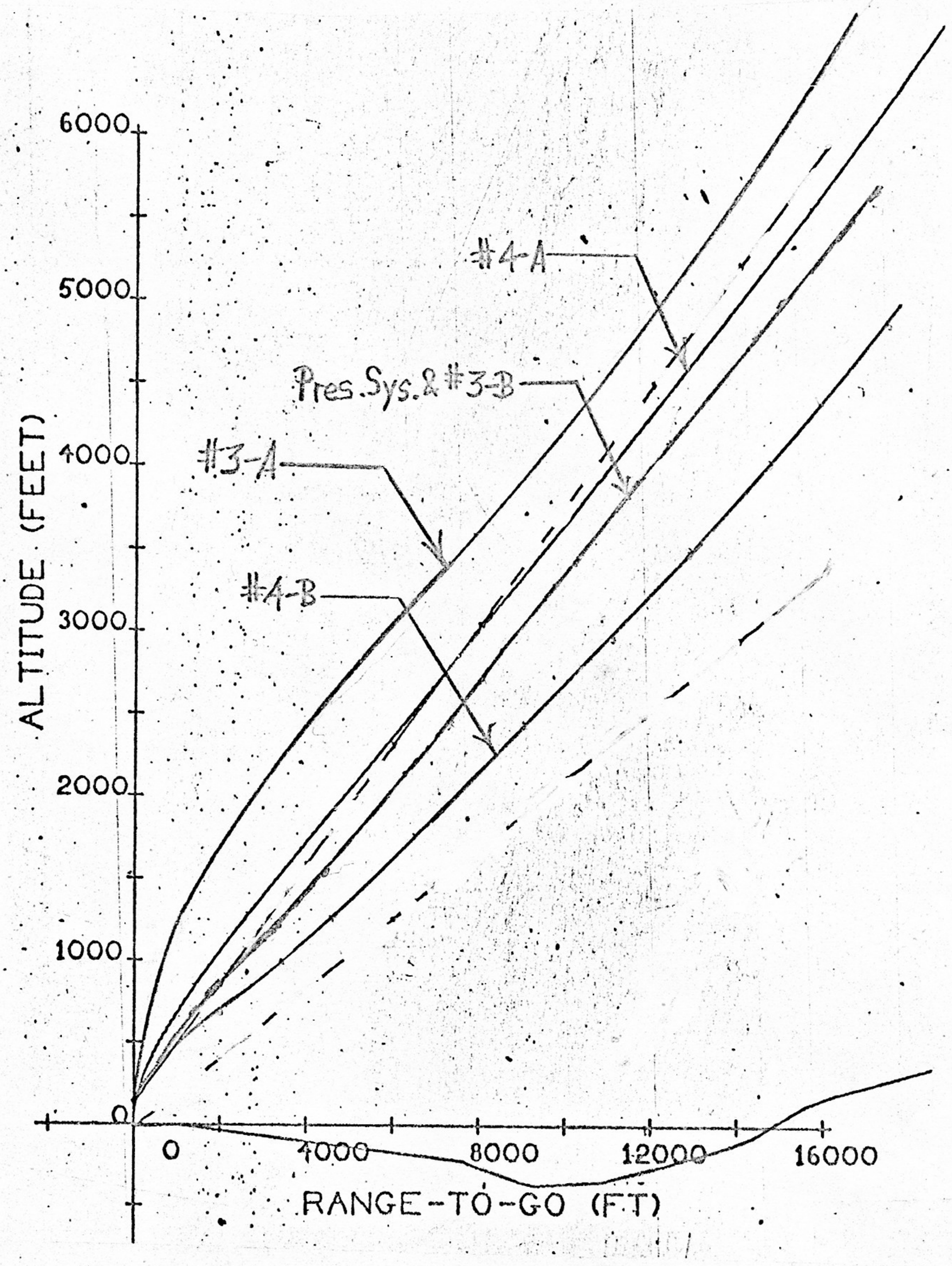


Fig. 20: Censorinus-C, Simple Stored Terrains

+ 1 degree slope
+ 10 f/s vert. vel. est error at PDI

+ slope = down-hill to site
+ vert. vel error: vehicle low

Filter	Run No.	ΔV (f/s)	HG Alt W.r.t. Site (ft)	Vel. at 500 ft. γ (deg.)	Vel. at 500 ft. Speed (f/s)	LPD Ang. Chars	Terminal H vs. RGO	Thrust Angle Profile	
Present System	785	6593	7280	−22.1	48	Good	Fair	Fair	2
#1	737	6652	7560	−28.3	38	Fair	Fair	Good	
#3-A	757	6997	8180	−58.5	20	Poor	Poor	Good	
#3-B (Slope est.)	753	6660	6517	−21.0	52	Poor	Good	Poor	
#4-A	709	6598	7565	−26.5	42	Fair	Fair	Good	3.
#4-B (Slope est.)	705	6597	7011	−13.9	57	Good	Good	Good	1.

Comments:

(1.) Runs 709 and 737 had the same ΔV at h=500 ft, Run 737 had an alt. est. error of 65 ft at this point whereas Run 709 had 21 feet

(2.) Present system oscillatory in thrust angle in P63, otherwise fairly good

(3.) Filter #3-A corrects altitude est. error too slowly, too high in P64

(4.) Filter #3-B too oscillatory in thrust-vector & LPD angles

(5.) Most favorable situation for #4-B slope estimator

Fig. 21: Performance of Simple Slope Estimator

Censorinus-B, Simple Stored Terrain, Filters #4-A & 4-B

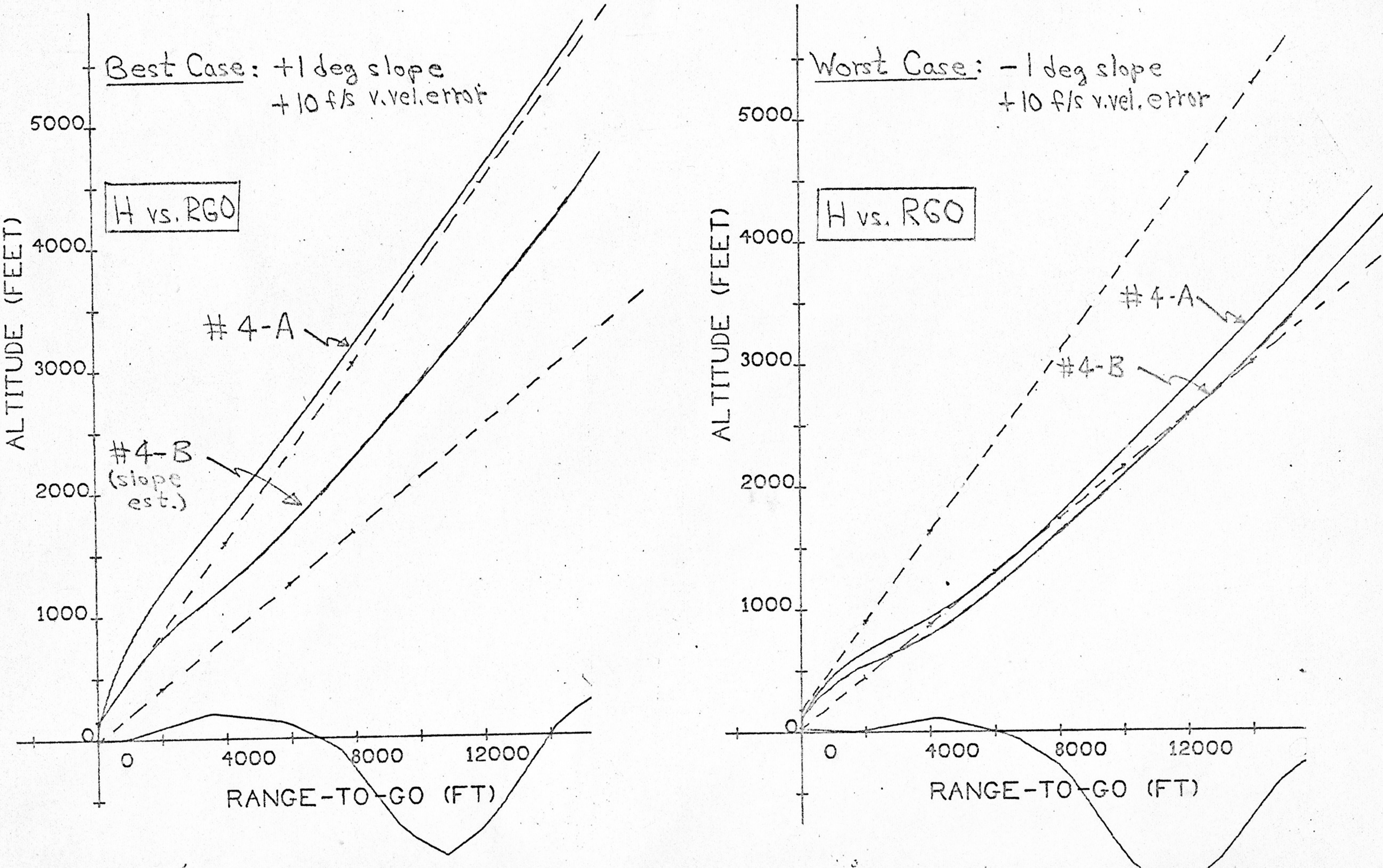


Fig. 22:

Summary of Results and Recommendations

(Based primarily on Censorinus B and C data)

- Store simple terrain model for approach phase to improve LPD profile and reduce LPD pointing errors

- Reduce altitude weighting function in braking phase to decrease pitch-angle oscillation, e.g. linear to 0.1: Trade-off terminal-phase trajectory constraints vs. pitch oscillations.

- Use weighting functions similar to present in approach phase to keep altitude estimation errors small

Filter Type	Pitch Profile	LPD Char.	Term. H vs RGO
Present System	Fair	Fair-Good	Good
#1	Good	Fair-Good	Fair
#3-A	Good	Poor	Poor
#3-B	Poor	Poor	Good
#4-A	Good	Fair-Good	Fair-Good
#4-B	Good	Fair-Good	Good

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